Using the 6dF galaxy redshift survey to detect gravitationally-lensed quasars

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Abstract

It is possible to detect gravitationally-lensed quasars spectroscopically if the spectra obtained during galaxy surveys are searched for the presence of quasar emission lines. The up-coming 6 degree Field (6dF) redshift survey on the United Kingdom Schmidt Telescope will involve obtaining $\sim 10^5$ spectra of near-infrared selected galaxies to a magnitude limit of $K = 13$. Applying previously developed techniques implies that at least one lens should be discovered in the 6dF survey, but that as many as ten could be found if quasars typically have $B_{\rm J} - K \simeq 8$. In this model there could be up to fifty lensed quasars in the sample, but most of them could only be detected by infrared spectroscopy.

Keywords: gravitational lensing – surveys – methods: data analysis

1 Introduction

Gravitationally-lensed quasars are very valuable. Individual lenses can be used to constrain the properties of the source, the distribution of mass in the deflector, and, through microlensing, the composition of the deflector. The frequency of lensing can be used to place limits on the cosmological model, and the distribution of image separations provides a useful probe of the average deflector mass. These and other uses of lenses are well known, but cases of multiple imaging are still rare ($\sim$ 50 known to date). This is not due to any lack of effort on the part of observers – most lenses are discovered by dedicated re-observation of previously identified high-redshift sources, but the likelihood of lensing is sufficiently low that imaging of up to $\sim$ 1000 fields is required per lensing event.

It is also possible to search for lenses spectroscopically, as opposed to morphologically. A small fraction of quasars are multiply-imaged by galaxies sufficiently nearby to make the composite object appear extended, whilst the quasar is bright enough for its emission lines to be apparent in the composite spectrum. Only one quasar lens – Q 2237+0305 (Huchra et al. 1985) – has so far been discovered in this manner, but the proximity of the deflector (a redshift 0.04 spiral galaxy)

has allowed a number of unique measurements to be made, as summarised by Mortlock & Webster (2000). Spectroscopic lens surveys will primarily be sensitive to these particularly useful systems, but the restriction that the deflector be so nearby also means that the frequency of such lenses is considerably lower than that of the general lens population (Kochanek 1992; Mortlock & Webster 2000). Thus a dedicated spectroscopic lens survey would be disastrously inefficient, but galaxy redshift surveys (GRSs) provide large samples of galaxy spectra as a matter of course. Such lens surveys are potentially very efficient, with the only data requirements being follow-up imaging of the best spectroscopic candidates.

Kochanek (1992) and Mortlock & Webster (2000) have already investigated the statistical likelihood of finding lensed quasars in redshift surveys. The 2 degree Field (2dF) GRS (Folkes et al. 1999) should contain at least ten lenses amongst its $\sim 2.5 \times 10^5$ spectra[1], and the larger Sloan Digital Sky Survey (SDSS; York et al. 2000), with close to 10^6 galaxies, may yield up to a hundred spectroscopic lenses.

These results are extended to the near-infrared-selected 6 degree Field (6dF) GRS here. The survey is described in Section 2, and the lens calculation is presented in Section 3. The results are summarised in Section 4.

2 The 6dF galaxy redshift survey

The 6dF instrument is a multi-fibre spectrograph for the Anglo-Australian Observatory's United Kingdom Schmidt Telescope (UKST). The largest project planned for the instrument is the 6dF GRS (e.g., Watson et al. 1998, 2000). This will involve obtaining the spectra of $\sim 1.2 \times 10^5$ galaxy candidates, as identified in the 2 Micron All-Sky Survey (2MASS; Jarrett et al. 2000), to a limiting magnitude of $K = 13.0$. About 175 nights of observing time will be required for the 6dF survey, which should be complete by mid-2003. The 6dF instrument can obtain 150 spectra simultaneously, but the integration time required is rather long, at about an hour, due to the small aperture of telescope ($\sim$ 1.5-m). The spectra will cover the range between 3900 Å and 7400 Å, with a resolution of 3.5 Å and a signal-to-noise ratio of ~ 10 per pixel.

The main scientific justification for the 6dF survey, given the existence of the 2dF GRS and the SDSS, is the near-infrared selection, as this relates directly to the old stellar population of the local galaxies. However there are several other distinctions important to the possibility of finding spectroscopic lenses. With a mean redshift of ~ 0.05 the 6dF GRS is considerably shallower than the 2dF sample, which has an average redshift of ~ 0.1. The 6dF spectra will have a similar signal-to-noise ratio per unit wavelength, but will cover a slightly smaller range.

3 Lens statistics

Mortlock & Webster (2000) contains a detailed description of how to calculate the number of spectroscopic lenses expected in a GRS. Briefly, one must integrate over the galaxy (i.e., deflector) and quasar (i.e., source) populations to find the number of lenses which satisfy the following three criteria:

- The total flux from the composite object (i.e., the sum of the light from the galaxy and quasar) must be brighter than the survey's flux limit.

[1] Effort is now underway to find lensed quasars in the 2dF spectra; this project, along with other spectroscopic lens searches, are described elsewhere in this issue by Mortlock, Madgwick & Lahav (2001).

- The quasar must be bright enough to be detectable in the spectrum of the lens.[2] Defining the summed quasar images' magnitude as m_{q} and the galaxy's magnitude as m_{g}, this criterion is taken to be satisfied if $m_{\mathrm{q}} \leq m_{\mathrm{g}} + \Delta m_{\mathrm{qg}}$ (Kochanek 1992). The value of Δm_{qg} depends on the quality of the data and the "distinctiveness" of the quasars' spectra.

- The galaxy must be sufficiently bright that the lens is identified as an extended source; it is this condition which ensures that only lenses with nearby deflectors are selected.

Figure 10 of Mortlock & Webster (2000) shows how the event rate increases with a survey's magnitude limit and Δm_{qg}, but these results apply to a B_{J}-selected GRS, whereas the 6dF sample is subject to a K-band flux limit. The target list, taken from the 2MASS survey, is also K-selected, but Δm_{qg} must be calculated in one of the optical bands (e.g., B, B_{J} V, R, etc.) covered by the 6dF spectra. A further complication is the paucity of available information about the quasar population at infrared wavelengths. These difficulties were circumvented by performing the calculation in the B_{J}-band (in order to facilitate comparison with Mortlock & Webster 2000), parameterising the deflector and source populations in terms of their $B_{\mathrm{J}} - K$ colours.

The B_{J}- and K-band galaxy luminosity functions measured, respectively, by Folkes et al. (1999) and Loveday (2000) are consistent provided the local galaxy population has $\langle B_{\mathrm{J}} - K\rangle \simeq 4$. Hence the 6dF GRS should be approximately equivalent to B_{J}-selected survey with a magnitude limit of ~ 17.

There have been no systematic K-band quasar surveys, but several attempts have been made to infer the luminosity function at these wavelengths from observations in other bands. Most quasar samples are selected using ultraviolet excess (UVX) methods (e.g., Boyle, Shanks & Peterson 1988), but dust obscuration at these wavelengths may result in serious incompleteness. UVX-selected samples typically have $\langle B_{\mathrm{J}} - K\rangle \simeq 2.5$, but the radio-selected Parkes Half-Jansky Flat-Spectrum sources (Drinkwater et al. 1997) are considerably redder, with $2 < B_{\mathrm{J}} - K < 10$ (Webster et al. 1995). These discrepancies should be resolved by upcoming infrared surveys (e.g., Warren, Hewett & Foltz 2000), but, for the moment, a range of $\langle B_{\mathrm{J}} - K\rangle$ values must be considered.

The uncertainty in the quasars' colours also affects the determination of Δm_{qg}, their spectral prominence in the survey data. The 6dF spectra will be of similar quality to those obtained during the 2dF survey, for which Mortlock & Webster (2001) estimated $\Delta m_{\mathrm{qg}} \simeq 2$. However this figure is relevant only if UVX-selected quasars are representative of the population as a whole. Whilst Δm_{qg} is calculated in the B_{J}-band, the 6dF spectra extend past V and R, almost to I, and quasars with $B_{\mathrm{J}} - K \simeq 6$ would be much more prominent in the red end (close to the I-band) of the spectra than UVX-selected objects. In terms of the model used here, this leads to an increase in Δm_{qg} by up to a magnitude, although the change depends on the exact shape of the galaxy and quasar spectra (specifically, their $B_{\mathrm{J}} - I$ colours).

The results of integrating over the deflector and source populations are given in Table 1. With optical spectroscopy the 6dF GRS should contain about 5 lenses if quasars are as red as inferred by Webster et al. (1995), but there would also be a large number of lensed quasars in the sample that are too red to be detected in the optical spectra. The only way to find these objects would be to obtain infrared spectroscopy of the entire sample; the likely yield from this procedure is also given in Table 1. In this case the increase of N_{lens} with Δm_{qg} is not as marked, as such a survey would probe magnitudes at which the quasar luminosity function was much flatter (e.g., Boyle et al. 1988)

[2] Note that the 6dF instrument's fibres are 6 arcsec in diameter, so that there is little distinction between the total magnitude and the fibre magnitude (as defined in Mortlock & Webster 2001) of an object. For spectroscopic lens searches small fibres – like those of the 2dF instrument – are desirable as they maximise the relative contribution of the quasar's light to the spectrum.

Table 1: Number of lenses expected in the 6dF GRS

	optical spectroscopy		infrared spectroscopy	
$\langle B_{\rm J} - K \rangle_{\rm quasar}$	$\Delta m_{\rm qg}$	$N_{\rm lens}$	$\Delta m_{\rm qg}$	$N_{\rm lens}$
2	1.5	0.3	0.0	0.02
4	2.0	1	2.0	1
6	2.5	3	4.0	14
8	3.0	7	6.0	27

4 Conclusions

Kochanek (1992) and Mortlock & Webster (2000) showed that several tens of lensed quasars could be discovered in galaxy surveys by examining the spectra obtained for the presence of quasar emission features. The 6dF GRS should contain at least one lens, but could yield as many as seven if quasars are typically very red (e.g., $\langle B_{\rm J} - K \rangle \simeq 8$; c.f. Webster et al. 1995). In this latter case the survey will in fact contain several tens of lenses, but most of these would only be detectable with infrared spectroscopy.

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